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Exhibit I

Fundamentals of PHYSICS

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press the wavelength in the medium as

$$\lambda_n = \frac{\lambda}{n} \tag{36-8}$$

where λ is the wavelength in vacuum.

Multiplying Eq. 36-7 by c/c gives the relative index of refraction between any two media as $n_{21} = n_2/n_1$, and the law of refraction becomes

$$n_1 \sin \theta_1 = n_2 \sin \theta_2. \tag{36-9}$$

Referring to Fig. 36-5*b*, we saw how two rays moving different distances, λ_1 in medium 1 and λ_2 in medium 2, nevertheless remained in phase; in other words the same number of wavelengths (in this case one) were contained in these distances. From Eq. 36-8 we can see that $n_1\lambda_1 = n_2\lambda_2 = \lambda$. This suggests that we define a quantity nl to be the *optical path length* of radiation traveling distance l in a medium of index of refraction n. This quantity, in effect, measures the number of wavelengths contained in distance l and is a useful quantity wherever phase differences between rays traveling in different media must be considered. The number of wavelengths contained in distance l is l/λ_n which, using Eq. 36-8 equals nl/λ. Thus, since λ is the fixed free-space wavelength, a condition that would insure that the same number of wavelengths are contained within distances l_1 and l_2 in two different media is

$$n_1 l_1 = n_2 l_2\,. \tag{36-10}$$

Equality of the optical path lengths thus implies no relative change of phase.

36-5 Total Internal Reflection

Let rays in an optically dense medium (glass, say) fall on a plane surface on the other side of which is a less optically dense medium (air, say); see Fig. 36-6. As the angle of incidence θ is increased, we reach a situation (see ray *e*) at which the refracted ray points along the surface, the angle of refraction being 90°. For angles of incidence larger than this *critical angle* θ_c there is no refracted ray, and we speak of *total internal reflection.*

The critical angle is found by putting $\theta_2 = 90°$ in the law of refraction (see

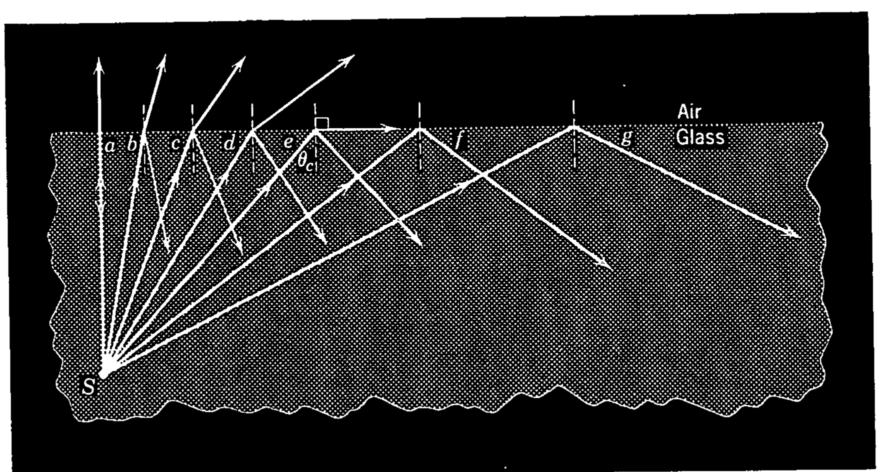

FIGURE 36-6 Showing the total internal reflection of light from a source S; the critical angle is θ_c.

Eq. 36–9):

$$n_1 \sin \theta_c = n_2 \sin 90°,$$

or

$$\boxed{\sin \theta_c = \frac{n_2}{n_1}.} \tag{36–11}$$

For glass and air, $\sin \theta_c = (1.00/1.50) = 0.667$, which yields $\theta_c = 41.8°$. Total internal reflection can not occur when light originates in the medium of lower index of refraction.

Example 3. Figure 36–7 shows a triangular prism of glass, a ray incident normal to one face being totally reflected. If θ_1 is 45°, what can you say about the index of refraction n of the glass?

The angle θ_1 must be equal to or greater than the critical angle θ_c where θ_c is given by Eq. 36–11:

$$\sin \theta_c = \frac{n_2}{n_1} = \frac{1}{n},$$

in which, for all practical purposes, the index of refraction of air ($= n_2$) is set equal to unity. Suppose that the index of refraction of the glass is such that total internal reflection just occurs, that is, that $\theta_c = 45°$. This would mean

$$n = \frac{1}{\sin 45°} = 1.41.$$

Thus the index of refraction of the glass must be equal to or larger than 1.41. If it were less, total internal reflection would not occur.

36–6 Brewster's Law

The laws of reflection and refraction give us information about the direction of reflected or refracted rays. They don't say anything about the intensities of these rays, except for the fact that the refracted beam intensity is zero for light striking at an angle equal to or greater than the critical angle. The complete intensity relationships can be derived from Maxwell's equations.* The derivation is somewhat difficult; however, from it you will find that the reflection coefficient (the ratio of the reflected intensity to the incident intensity) not only depends upon the angle of incidence but also upon the direction of polarization of the incident beam. Similarly for the refracted beam.

Malus discovered in 1809 that light can be partially or completely polarized by reflection. Anyone who has watched the sun's reflection in water, while wearing a pair of sunglasses made of polarizing sheet, has probably noticed the effect. You need only to tilt your head from side to side, thus rotating the polarizing sheets, to see that the intensity of the reflected sunlight passes through a minimum.

Figure 36–8 shows an unpolarized beam falling on a glass surface. The **E**-vector for each wavetrain in the beam can be resolved into two components, one perpendicular to the plane of incidence (the plane of Fig. 36–8), represented by dots, and one lying in this plane, represented by arrows. We shall call

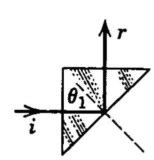

FIGURE 36–7 Example 3.

* See Chapter 11 "Plane Waves—The Influence of the Medium" in *Intermediate Electromagnetic Theory* by W. M. Schwarz, John Wiley and Sons, New York, 1964.